Rapid Development of Instrument Thermal Models: Perspectives and Guidelines from NASA Goddard's Instrument Design Laboratory

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The Instrument Design Laboratory (IDL), part of NASA Goddard Space Flight Center's Integrated Design Center (IDC), is a concurrent and collaborative environment which allows for rapid development of science instrumentation concepts within the span of less than two weeks. Science goals set by a Principal Investigator from government, industry or academia are translated into engineering requirements, from which a team of engineers spanning multiple disciplines use an established study process and a suite of analysis tools to work towards an instrument point design. As part of this process, a staff thermal engineer is tasked with designing a thermal control system which meets all incoming thermal requirements, while iterating real-time with other subsystems to ensure compatibility and functionality as a completed system. Thermal engineers on spaceflight projects typically have weeks or months to develop thermal models. However, the severe time limitation in this conceptual study setting makes thermal design particularly difficult, as rapid thermal modeling solely over the span of a few days is required to develop the instrument thermal design and understand the performance over its intended mission, especially if the instrument concept contains multiple thermal challenges such as dynamic environments or high heat dissipating components. In this paper, the authors provide a condensed guide for the most efficient ways to develop thermal models and conduct thermal analysis within the span of one-to-two weeks, as informed by decades of design experience and best practices in the IDL. The authors also focus on quick methods for determining worst-case thermal environments, deciding which modeling details are essential at this early phase, and quantifying the engineering resources necessary for thermal control. This paper concludes with specific thermal design tips for different instrument types across the electromagnetic spectrum.

Nomenclature

α	=	absorptivity
ε, ε^*	=	emissivity, effective emissivity
FEE	=	Front End Electronics
IDL	=	Instrument Design Laboratory
IEB	=	Instrument Electronics Box
IR	=	Infrared
MLI	=	Multi-Layer Insulation
μm	=	micrometer (10^{-6} m)
nm	=	nanometer (10^{-9} m)
pm	=	picometer (10^{-12} m)
RF	=	Radio Frequency
UV	=	Ultraviolet
W	=	Watts

I. Introduction

THE design and development of robotic spaceflight instruments is a critical part of NASA's vision to discover and expand knowledge for the benefit of humanity. In service of this goal, NASA maintains multiple design laboratories across its field centers to conceptualize instruments which make measurements across the electromagnetic spectrum. Engineers spanning a variety of disciplines come together within these labs to translate scientific goals to spaceflight hardware and software, developing first-cut designs for proposal and quantifying all of the engineering

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resources required to make an intended measurement. At NASA's Goddard Space Flight Center, the Instrument Design Laboratory (IDL) uses a collaborative and concurrent design process sharpened over two decades to rapidly develop instrument solutions which are consistent across multiple disciplines. Thermal engineers are an integral part of this process, performing rapid analysis and identifying thermal control methods over the course of a week-long study to facilitate the design team's progress towards a closed solution.

For typical spaceflight instrument projects, thermal engineers may be given months or years to develop and refine a thermal solution. However, rapid thermal design for instrument concepts, whether for proposals or trade studies at an early stage of a project, do not enjoy the luxuries of time and numerous design iterations. Often, a Principal Investigator (PI) arrives solely with a set of science goals for an intended measurement at a specific wavelength, requiring an instrument type which may be novel or unfamiliar to the thermal engineer. In these cases, how would the thermal engineer approach the problem or examine multiple possible instrument configurations within a short time? This current work is intended to fill a gap in understanding of the tall poles and design drivers for early instrument design from a thermal perspective, providing a condensed guide for the most efficient way to develop thermal models and conduct thermal analysis within one to two weeks, and including what would be important and unimportant to model at these early stages. The guidelines originate from the experience and lessons learned from hundreds of instrument studies across the IDL's history. This work is organized into two major sections: an introduction of the rapid thermal design process, followed by specific guidelines for various types of instruments across the electromagnetic spectrum.

II. Rapid Thermal Design Process

The rapid thermal design process as described in this section was derived from and developed in conjunction with the abbreviated study schedule for the IDL. It is aimed towards the development of thermal models within one to two weeks assuming that all discipline engineers for which the thermal engineer needs to achieve design compromises with are available concurrently during those weeks to collaborate on the design. It consists of the following steps which will be described in detail in the subsections below:

A. Determine Boundary Conditions
B. Determine Worst-Case Thermal Environments
C. Gather Thermal Inputs from Other Disciplines
D. Determine Your Temperature "Zones"
E. Build a Preliminary Thermal Model
F. Iterate Technical Design with Other Disciplines
G. Perform Model Checks and Obtain Thermal Analysis Results

A. Determine Boundary Conditions

The gathering of thermal requirements is paramount in the early stages of rapid thermal design and steps A through D target establishing those requirements from the separate engineering disciplines. For spaceflight instrument design, the most critical mechanical interface is with the spacecraft, as this provides the basis for instrument thermal design. The thermal engineer first needs to establish where the instrument is mounted with respect to the spacecraft; if a particular spacecraft has not yet been chosen, the thermal engineer can made assumptions as to spacecraft interface temperature and orientation with respect to the bus, which can be held as liens during spacecraft selection. Establishing a common coordinate system also allows for easy reference with other discipline engineers, especially if the intent is to be consistent with other major analytical models. For the IDL, it is also required of any incoming instrument that its optical or RF designs, comprising the scientific heart of the instrument, have their relative component positions solidified with respect to each other, and the sensitivities of mechanical tolerance understood. This is crucial prior to commencing any thermal modeling, as even small changes may result in vastly different mechanical packaging and thermal control methods.

B. Determine Worst-Case Thermal Environments

The goals for scientific observation from the intended instrument drives the orbit and worst-case thermal environments. For rapid thermal analysis, a simple cube model is sufficient to discretely quantify temperature changes due to heat flux on each side of the spacecraft. In thermal software, heat fluxes can be quantified by a six-node cube with one arithmetic node on each side of the cube and perfect blackbody optical properties. By placing this model

within the intended orbit, the thermal engineer can quickly examine worst-case hot and cold conditions to design to. The heat fluxes per side per orbit can also determine which sides are suitable for radiators, and which require MLI. If thermal stability is a concern, a cube model additionally serves as a good testbed for materials and their corresponding thicknesses to achieve the desired thermal mass and stability. If resultant temperatures the "cold" faces of the cube do not achieve the intended sinks for passive thermal control, the thermal engineer can quickly add surfaces representing Earth shields, planetary shields, or sunshields until such temperature is achieved. In more unique environments such as for planetary landers, more initial information is required to establish worst-case thermal environments, including: atmospheric composition and convective coefficients at different atmospheric layers; cold sky temperatures; average ground temperatures; and position of the sun or other celestial bodies as a vector list versus time.

C. Gather Thermal Inputs from Other Disciplines

The requirements for the thermal design are in large part driven by the hardware requirements and design choices of other subsystems. Table 1 lists engineering disciplines that are typically present at early concept phases for an instrument, and which inputs the thermal engineer needs to source from these disciplines for their own assessment.

Engineering Discipline	**Thermal Inputs**
Attitude Control	Sun avoidance angle, pitch/roll/yaw angles
Detectors and Electro-Optical	Temperature requirement, temperature stability requirement, power dissipation, quantity, geometry and dimensions, mass, coatings
Electrical	Number of boxes, power dissipation, dimensions, mass, temperature requirement
Mechanical	Mechanical packaging, geometry, dimensions, mass, material, location of boxes, spacecraft thermal interface information, radiator placement
Optical	Temperature requirement, stability gradient requirement, quantity, geometry and dimensions, mass, coatings
RF/Microwave	Power dissipation, temperature requirement, stability or gradient requirement
Reliability	Redundancy requirement, temperatures desired to maximize reliability
Structural	Material selection, material thickness
Systems	Point Design Summary (PDS), orbital parameters, mass/power allocations for thermal components (if applicable)
Contamination	Specific thermal coatings and degradation, outgas heater if required
Cryogenics	Cryocooler compressor power dissipation, temperature requirement, Cryocooler cold head temperature, ADR and cryocooler thermal interfaces
Integration &T Testing	Special GSE e.g., Helium sink
Lasers	Power dissipation, temperature requirement, temperature stability requirement
Mechanisms	Temperature requirement, geometry, dimensions, power dissipation
Power	Battery temperature requirement, power profile

Table 1. Thermal Inputs Provided by Typical Instrument Disciplines

D. Determine Temperature "Zones"

Temperature zones are a useful tool as they help the thermal engineer group components that have similar thermal requirements for ease of design. Establishing temperature zones requires the information gathered from the separate discipline engineers in the previous step to be parsed to understand which components have similar thermal requirements. From the information gathered on operational and survival limits, gradient requirements, and stability requirements, the thermal engineer would then decide which components can be grouped together to the same method of thermal control, saving on complexity in the thermal design. Temperature zones also help identify areas where

thermal control may be challenging. Figure 1 below shows a sample temperature zone block diagram for an optical instrument.

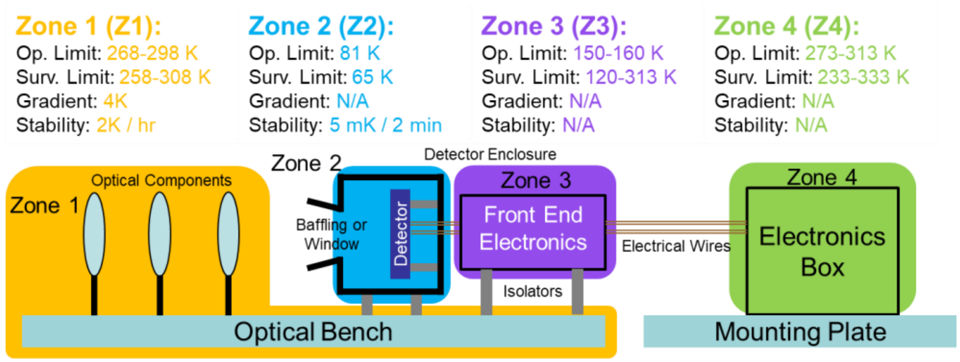

Figure 1. Temperature Zone Example for an Optical Instrument

Table 1 below shows typical component temperatures for spaceflight instruments as a quick reference. Please note that these are solely examples which may be used for early conceptual design, especially when a requirement for a certain box or component is missing. However, each piece of spaceflight hardware is unique and has different temperature requirements based on the vendor. As the instrument design progresses and is reiterated, vendors will customize their own thermal requirements for a component or assembly, and vendor data will override what's presented in the tables below.

Component	**Typical Temperature Ranges (°C)**				**Stability range (if applicable)**
	Operational		**Survival**		
	Min	**Max**	**Min**	**Max**	
Electronics Boxes (Including Cryocooler Control Electronics, Digital Signal Processors, and Laser Control Electronics)	-10	40	-40	60	
Antennas	-100	100	-120	120	
Batteries	0	25	-10	35	
Mechanisms	10	40	-40	60	
Optical or Laser Bench (Near-IR, Visible, UV; often require stringent thermal stability)	5	35	-20	40	± 2
Lasers (often require stringent thermal stability)	20	40	-20	60	± 1
RF Components (Analog)	-10	40	-25	60	± 2
Cryocooler Thermo-Mechanical Units	5	45	-35	70	
X-Ray Sources	0	30	-20	50	

Table 2. Example Instrument Component Types and Temperature Requirements

A list of typical operational temperature ranges and stability requirements for detectors across the electromagnetic spectrum can be found in Table 2. Detectors in this table are categorized by wavelength range and detector types; note that for UV and X-Ray instruments, there are multiple detector categories corresponding to science objective, and the operational temperatures and stability requirements are tied to these specific categories. In addition, the values in this table are solely representative of requirements typical to each wavelength from a survey of the IDL's previous studies. Each spaceflight instrument is different and detector temperature is highly dependent on the science goals, the wavelengths to be measured, and temperatures needed to achieve acceptable radiometric performance; the ultimate

source of detector temperature requirements should come from the principal investigator, radiometric engineer, and detector engineer or detector vendor.

Wavelength Range	Portion of Electro-magnetic Spectrum	Example Detector Types	Typical Operational Temperatures (K)		Thermal Stability Requirements (K/hr)	
			Low	High	More Stringent	Less Stringent
> 1 mm	Microwave and RF	Microwave / RF Receivers	260	310	± 0.1	± 2
25 µm - 1 µm	Sub-mm wavelengths / Terahertz range	Heterodyne Receiver (SIS, HEB), TES bolometers	< 1	40	± 0.1	± 1
2.5 µm - 25 µm	Mid-Infrared to Far-Infrared	HgCdTe, TES, Ge:Ga Photoconductors	< 1	100	± 0.001	± 1
750 nm - 2.5 µm	Near-Infrared	HgCdTe, InGaAs, InSb, STJ, TES, Si < 1100nm	50	170	± 0.001	± 1
400 nm - 750 nm	Visible	Si CCD, Si CMOS, photodiodes, STJ	170	340	± 0.005	± 1
1 nm - 400 nm	Ultraviolet	GaN, MAMA, Microchannel	270	340	± 0.005	± 1
		EMCCD, CCD, CMOS	170	200	± 0.001	± 1
1 pm - 1 nm	X-Ray	Gas-filled, Scintillation, Microchannel, CdZnTe	270	330	± 0.1	± 5
		CCD, CMOS	170	200	± 0.001	± 1
		TES	< 0.1	1	± 0.0005	< ± 0.001
< 1 pm	Gamma Ray	CMOS, Scintillator, CsI, SiPM, CCD, Strip Detectors	80	300	± 0.1	± 1

Table 3. Example Detector Types and Temperature Requirements

E. Build a Preliminary Thermal Model

Steps A through D focused on the gathering of thermal requirements both from science goals and concurrent work from other discipline engineers. This information coalesces at the development of the preliminary thermal model, and the rapid nature of this development comes from an understanding of what needs to be modeled at this early stage, what can be assumed, and what can be omitted. This step presents general model-building guidelines and best practices. Modeling guidelines for specific instrument types are captured in Section III.

Prior to development of a specific instrument model, a few readied items will greatly facilitate the rapid generation of a thermal model: a list of common thermo-physical and optical properties; a list of common thermal conductances, especially regarding thermal interface materials; and a template thermal model file populated with simple shapes in primitives and shells, including rectangular prisms, cylinders, flat plates, disks, and a basic heat pipe model. These shapes can be then repositioned, rotated, and re-dimensioned to match an initial mechanical CAD file when it becomes available. The CAD design does not need to be finalized; indeed, assumptions can be made and generic values can be used for interfaces that are not yet well-defined. A good initial assumption for contact conductances for non-isolated interfaces is 0.8 to 1.0 W/m^2K, while for conductors it is 1-5 W/K for well-coupled and < 0.1 W/K for isolated interfaces. Primitive shapes are also preferred over finite elements as they can be resized and re-discretized easily. Heat loads should be applied to surfaces rather than nodes. If your thermal modeling software supports it, use symbols for quick modification of parameters later. In early thermal analysis, steady state is also preferred over transient analysis unless the orbit or mission being modeled is extremely transient in nature, such as a descent trajectory.

Table 4 provides mass and power guidelines for common thermal hardware, and Table 5 provides environmental fluxes and parameters for worst-case hot and cold design cases in Low-Earth Orbit. It should be noted that, when sizing radiators, the hot case should be used, while the cold case should be used to size heaters. For a survival case, heat loads should reflect a reduced operational configuration so that the heater powers calculated are sufficient to meet survival limits.

	Mass	Power	Comments
Multi-Layer Insulation	0.73 kg/m^2	0 W	Based on 15 layers
Kapton Heaters	0.36 kg/m^2	Various, based on heater power requirements	Based on 10-mil thick Kapton heaters
Thermostats	6 grams each	0 W	
Thermal Sensors	1-3 grams each	~0 W	
Heat Pipes (Ammonia)	0.15 kg/m	0 W for Constant Conductance Heat Pipes ~10 W for Variable Conductance Heat Pipe (VCHP) Control	Mass per unit length Add 1-3 kg each for VCHP reservoirs
Loop Heat Pipe Evaporator	2-5 kg	10-30 W Control Power	
Radiator Panels	3.3 kg/m^2	0 W	Mass based on Aluminum Honeycomb radiator Add heat pipe mass if embedded
Electronic Controllers	0.2 kg	1-3 W each	

Table 4. Common Masses and Powers for Thermal Hardware

	Hot Case	Cold Case
Solar Flux	1412 W/m^2	1322 W/m^2
Albedo	0.35	0.25
Earth IR	267 W/m^2	211 W/m^2
Component Power Dissipation	Max.: Head Load with Contingency	Min./ Off: Heat Load Best Estimate (No Contingency)
MLI Blanketing	Less effective emissivity on cold side, $\varepsilon^* \approx 0.01$	More effective emissivity on cold side, $\varepsilon^* \approx 0.05$
Radiator Coating	End-of-Life Properties (higher α, lower ε)	Beginning-of-Life Properties (lower α, higher ε)

Table 5. Common Environmental Fluxes and Design Parameters for Low-Earth Orbit

F. Iterate Technical Design with Other Subsystems

As part of a dynamic instrument design process, especially in the early stages of concept design, thermal design can be simplified or thermal challenges mitigated with design compromises with other engineers. Often, difficulties in thermal design which arise in later project phases could have been mitigated early on with a conversation to reposition a high heat-dissipating component close to a radiator, or to loosen a stringent requirement without greatly impacting instrument performance. The topics in Table 6 are presented assuming flexibility of the instrument design and the ability to access separate discipline engineers for design iteration.

Topic of Design Iteration	Dependencies	Areas of Pushback if This Becomes a Concern
Radiator: Size, Location, Material, Coating	Orbit (ACS), Available Volume (Mechanical), Available Mass (Mechanical)	Are there other faces where additional radiators can be placed? Can volume allocation increase? Can the radiator be thicker or have heat pipes embedded? Can operational loads be reduced or temperature requirements be made less stringent?
Heater: Size, Power, Placement	Available Power (Electrical/Power), Temperature Constraints (All Disciplines)	Can temperature requirements be made less stringent? Can Electrical provide more power? Can the heater be placed closer to the component or directly on the component? Can Electrical accommodate more heater services?

Thermal Transport or **Thermal Isolation:** Size, Location, Material	Temperature/ Gradient/ Rate Constraints (All Disciplines), Placement and Available Mass (Mechanical)	Can temperature limits, stability, or gradient requirements be made less stringent? Can the placement be changed for a certain thermally challenging component?
Cryogenic Components: parasitics to cryogenic temperature zones, cryocooler heat rejection, location of temperature intercepts	Temperature/ Gradient/ Rate Constraints (All Disciplines), Wires / Harnesses (Electrical), Placement and Available Mass (Mechanical)	What design compromises between cryogenic isolator A/L can be achieved with the structural engineer? Can windows to a cryogenic enclosure be made smaller to minimize radiative parasitics? What wire material choices can be made to minimize conductive parasitics? Can component heat dissipations be smaller? Can cryocoolers / CCEs be positioned optimally for thermal control?
Thermal Sensors	Electrical Architecture	Can more thermal sensors be accommodated by Electrical?

Table 6. Design Iteration Recommendations for Thermal Hardware

G. Perform Model Checks and Obtain Thermal Analysis Results

Once a preliminary thermal design is established, the following analytical model checklist helps identify any errors prior to running the model in the intended hot and cold cases:

- Is the instrument oriented correctly with respect to the orbit?
- Are all of the nodes connected in the model?
- Are there any duplicate nodes or surfaces? Overlapping or coplanar surfaces?
- Check active sides and optical properties: do they appear as expected?
- Are MLI nodes on the correct sides? Are they arithmetic? Do they have correct ε* values?
- Do contactors make contact as expected? Are they connecting the correct sides or edges?
- Are the correct power dissipations applied in the correct cases?
- For spinning components or articulators: are the correct surfaces spinning? When the articulator is set to a different value, do the correct surfaces move?
- Are any view factor sums not close to 1, or thermal masses much higher than average?
- Are heaters controlling to the expected temperatures? Are any heaters saturated?

After thermal model accuracy has been verified, allow thermal models to run for the suite of hot and cold cases. Through plots of temperature contours or temperature vs. time for transient cases, ensure that resultant temperatures and heat flows are consistent for what's expected for the given environment, and identify any temperature outliers for additional scrutiny. Evaluate thermal analysis results with the goal or deliverable in mind: does the model sufficiently capture temperature extremes and heater powers? Is it able to quantify the engineering resources and thermal hardware required to achieve the desired control?

This current section has focused on modeling best practices to rapidly develop thermal designs and evaluate their effectiveness via analysis. The next section addresses specifically the tall poles and details to be incorporated in thermal models for each instrument type.

III. Specific Rapid Instrument Thermal Design Examples

The completion of hundreds of instrument studies over the IDL's two-decade history has allowed for identification of general tall poles and lessons learned for instruments across the electromagnetic spectrum, from Radio Frequency / Microwave instruments, to Optical instruments in the Infrared (IR), Visible, and Ultraviolet (UV) ranges, to X-Ray and Gamma Ray instruments. Presented below are brief design recommendations for each type of instrument, including specific design drivers pertaining to the that instrument type which have not been covered in the general design section above.

Microwave and Radio Frequency (RF) Instruments

Microwave and RF instruments describe those which measure in wavelengths greater than 25 micrometers (μm, 10^{-6} m) and include both RF/Microwave receivers and the sub-mm Terahertz range group of instruments. These

instruments often consist of a large antenna, a feedhorn, an analog RF receiver, and potentially a back-end digital processor. As the antenna and feedhorn placements are fixed relative to each other and represent a critical dimension, thermal design typically takes place after the design of these major components are solidified. Antennas are often polished mirrors, large booms, or large deployable meshes, and require minimal thermal control except for the mechanisms that may be used to deploy these structures. However, their dimensions and optical properties need to be well-captured for radiation models, and especially transmissivities for mesh or film antennas. Feedhorn temperatures may be allowed to float with their environment as long as they have a thermal sensor for temperature knowledge in calibration, but waveguides downstream of the feedhorn linking it to an RF receiver may have strict operational and temperature stability requirements. These can be modeled as tubes, similar to propulsion lines, and controlled in a similar fashion with blanketing and line heaters.

In an RF receiver, at an early stage of thermal design, individual RF components do not need to be modeled: they are integrated as part of a box or bench, and the conglomeration of their heat dissipations spread over their box or bench provides sufficient thermal model resolution. Waveguides linking these RF components can just be agglomerated in the RF box or bench mass as well. These boxes or benches, however, may need to be controlled to strict thermal stability requirements to ensure consistent RF performance upstream of the first low-noise amplification stage, especially if intended instrument is a radiometer. Furthermore, downstream electronics boxes to digitize or process the RF signal or remove RF interference should be treated with similar operational and survival temperatures as other digital electronics boxes; these digital signal processors may have proximity requirements to the RF box or bench if their input signals are analog. If this is the case, there may be a succession of multiple high-heat-dissipating boxes next to each other; aim to use a common radiator if possible.

For active RF instruments, such as radars, the thermal drivers tend to be high dissipation transmitter components, such as power amplifiers and power distribution units. Many active and passive systems also use a rotating antenna reflector: while their view factors can be sufficiently captured with a "fast spin" option for thermal modeling software, the drive mechanisms behind these mechanisms can be a large source of heat. Many active and passive systems also use external calibrators, such as "cold" targets which view deep space "hot" targets which require a strict operational temperature and stability. Figure 2 shows a sample RF/Microwave Instrument System with possible MLI and heater placements.

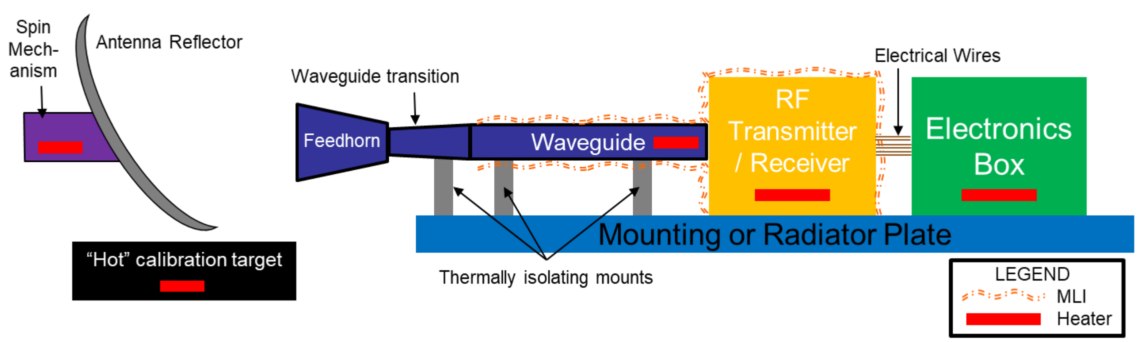

Figure 2. Example Active RF and Microwave Instrument Thermal Design

Infrared, Visible, and Ultraviolet Optical Instruments

Optical instruments use lenses, mirrors, filters, gratings, and other optical components to image or determine the characteristic properties of objects typically emitting in the infrared (750 nm - 25 µm), visible (400 nm - 750 nm), and ultraviolet (1 nm - 400 nm) portions of the electromagnetic spectrum. Infrared (IR) instruments, especially those that measure in the mid- to far-IR, typically require cryogenic operational temperatures and strict temperature stability requirements on their detectors, while visible and ultraviolet (UV) instruments may have detectors closer to room temperature and looser stability requirements. In the IDL, one of prerequisites for thermal design is to ensure that the optical design is "frozen" prior to any thermal assessment. As changes to optical component placement may have huge impacts for detector selection and the temperature sensitivities of optical components, establishing thermal "zones" becomes exceedingly difficult with the optical design in flux.

While IR, visible, and UV instruments each have very different driving requirements depending on the instrument type – imager, interferometer, polarimeter, reflectometer, spectrometer, etc. – a few high-level design guidelines are common to instruments which operate in this part of the spectrum. Detectors tend to have the strictest thermal requirements of any instrument component, and the focus and challenge of the thermal design primarily resides in control of the detector housing or enclosure. For optical components at this early stage, unless they are large (such as primary mirrors on telescopes), isolated (such as secondary mirrors), or have extremely tight thermal control requirements, their geometries typically do not need to be modeled. These individual optical components have little impact on thermal design, and thermal control can be focused on the bench or benches in which they are mounted. In addition, scan mechanisms or others requiring constant actuation may require careful design to isolate their heat loads from the sensitive optical components in which they are actuating, while mechanisms which have low duty cycles or have one-time actuations may not need to have their heat loads modeled at all.

Detector temperature requirements and stabilities, such as those presented Table 3, dictate the complexity of the detector housing or enclosure and the difficulty of thermal control for the instrument. Simplicity of thermal design is desired, and passive cooling is always preferred if achievable. To facilitate passive cooling and mitigate parasitic heat loads to the detectors, certain design features can be discussed early in the instrument design process with other engineers: with an optical engineer, the sizing of baffles and windows to the detector can be determined which minimize radiative parasitics while ensuring sufficient optical signal; with a structural engineer, the acceptable materials and A/L of detector supports can be compromised upon to minimize conductive parasitics while ensuring sufficient structural rigidity; with an electrical engineer, the electrical wiring material to the detector and its cross-sectional area can be negotiated to further minimize conductive parasitics while ensuring sufficient electrical signal. Passive thermal control may also hinge upon the ability for the detector to be placed close to a radiator to allow for conductive heat transfer via a thermal strap; if an early design compromise can be achieved with the optical engineer such that the optical design can be oriented or a fold mirror can be added to position the detector close to the "cold" side of the spacecraft, these early decisions contribute greatly to the facility of thermal design in future iterations.

Challenging detector requirements may necessitate the use of active thermal control using a thermo-electric cooler (TEC) or cryocooler. Both devices require management of their non-trivial heat dissipations, and for mechanical cryocoolers these may require a separate radiator to reject the heat of both its thermo-mechanical unit and control electronics. Detector Front-End Electronics (FEEs), which typically perform readout, digitization, and amplification of detector signals prior to entry into an instrument electronics box (IEB) or computer, are often kept at an intermediate temperature zone between the IEB and detector despite proximity to the detector itself, and require less stringent thermal controls. Figure 3 shows an example of an optical instrument with an actively cooled detector (via a mechanical cryocooler) and front-end electronics. While there is a recent trend to perform digitization using on-chip Digital readout integrated circuits (DROICs), careful consideration must be made between the thermal and detector engineers to balance readout convenience with thermal challenge, as DROICs result in much higher heat dissipations for the detector package while occupying the same cryogenic temperature zone. If the detector requires single or sub-Kelvin temperatures, these present unique thermal challenges due to multiple required stages of thermal cooling, the use of Adiabatic Demagnetization Refrigerators or other active cooling hardware, or limits in lifetime from the use of cryogenic consumables. For these sub-Kelvin detectors, careful bookkeeping of parasitics is critical to thermal management.

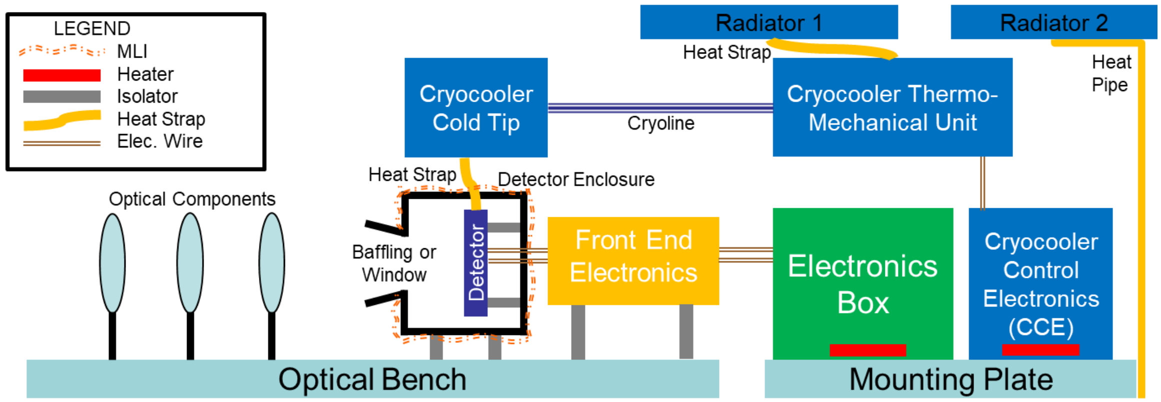

Figure 3. Example Actively Cooled Optical Instrument Thermal Design

In addition, if the optical instrument relies on laser transmission for its measurement, such as in a Raman spectrometer or altimeter, this primarily impacts the thermal design by imposing stricter thermal stability limits on the optics and requiring management of the significant heat dissipations from the laser heads and laser control electronics. For vendor-procured lasers, these often contain their own internal thermal management within the laser heads and require an interface maintained at a specific temperature range to manage the volume of heat output by the laser itself. Management of these interfaces can be achieved with heat pipes to dedicated radiators. However, in cases of strict stability requirements or very large heat dissipations, complexity of the thermal management system may scale with requirements and necessitate a loop heat pipe, pumped fluid loop, or other elaborate thermal control methods.

X-Ray and Gamma Ray Instruments

X-Ray instruments encompass those which measure in wavelengths between 1 picometer (pm, 10^{-12} m) and 1 nanometer (nm, 10^{-9} m), while Gamma Ray instruments occupy the range shorter than 1 pm wavelength. The highly energetic nature of these particles drives instrument design, and indeed X-Ray instruments often have the most challenging thermal requirements to design to. X-Ray instruments tend to be designed in two parts: a telescope assembly at the front end and a separate sensor or detector assembly at the focal plane. These may be separated by large distances to allow x-rays to focus with grazing incidence reflection from the telescope, yet require tight thermal control within each respective assembly and between assemblies to ensure alignment. On the telescope assembly side, common focus optics include concentric rings at different angles (a Wolter Telescope design), requiring tight gradient requirements and active heater control to achieve uniformity and stability in temperatures. On the detector assembly side, X-Ray detectors tend to have large collecting areas and high dissipation, yet require extremely tight stabilities and potentially cryogenic temperature ranges. In X-Ray systems, the type of detector and the temperatures required for sufficient signal greatly impact the detector enclosure design and cooling method. For those which require cryogenic systems, implementation is similar to the actively cooled and sub-Kelvin designs for optical instruments in the section able. An example of a passively-cooled X-Ray instrument is shown in Figure 4. In this example, the telescope assembly and its series of concentric rings have their gradients controlled by a series of heaters blanketing each ring structure. On the detector side, the X-Ray filters and detector enclosure are mounted on a common optical bench. The multiple X-Ray detectors are mounted on a common cold-biased plate with precise heater control (possibly proportional-integral-derivative) to allow their temperature stability requirements to be met while maintaining uniformity of temperatures across detectors. While the FEE occupies the same detector enclosure, they are isolated from the detector plate to reduce parasitic heat leaks and impact on detector plate heater control, as likely the FEE does not require as tight of a temperature control as the detectors themselves. This enclosure is tied to a heat pipe which siphons heat to a dedicated radiator.

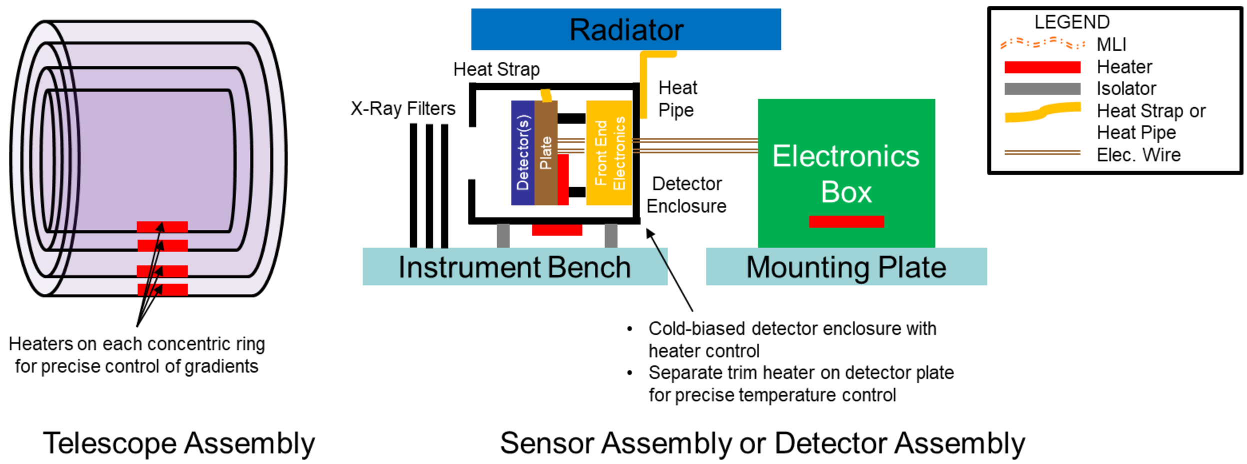

Figure 4. Example of a Passively-Cooled X-Ray Instrument Thermal Design

Unlike X-Ray instruments, Gamma Ray instruments cannot rely on optics to focus gamma rays on a single detector. Instead, Gamma Ray instruments typically carry large numbers of detectors arranged in stacks of trays to detect gamma ray "hits" and determine their trajectory. Due to the sheer numbers of detectors, heat dissipations are extremely high for these types of instruments, but normal thermal management techniques may not work as they require low Z-energy materials to minimize background noise, which excludes the many metallic components that thermal control hardware is often made from. If stacked detector trays are used for these designs, thermally conductive carbon composites and epoxies are essential materials, and thermal design must be optimized at the tray level to ensure adequate thermal control and heat rejection, as small changes or increases in heat will result in large impacts on thermal performance of the entire system when propagated to all trays. On a systems level, electrical harness conductance must be considered as a significant vehicle for heat transport, and for certain cases metallics are unavoidable such as in utilizing heat pipes to transport the large volumes of heat from the tray towers. For Gamma Rays, both the tray-level and instrument-level optimizations are important for thermal management of the entire system.

IV. Conclusions

This current work presented the thermal design processes of NASA Goddard's Instrument Design Laboratory as a guideline for rapid thermal design and analysis. A general modeling guideline was established with discrete steps to rapidly achieve analytical results, and specific tall poles and lessons learned were presented for instrument types across the electromagnetic spectrum. While each spaceflight instrument is different and its thermal requirements reflect the intended science, it is hoped that this work provides a general guideline for thermal engineers working in a rapid instrument concept environment to: obtain thermal requirements, identify thermal worst-cases, coordinate with other discipline engineers, and include solely necessary details.